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ABSTRACT

In this paper, we introduce a general framework for waveform design and signal processing, dedicated to the study of turbulent flow phenomena. In a bi-static configuration, by transmitting a specific waveform with a predefined instantaneous frequency law (IFL), within the bounds of the Kolmogorov spectrum, the turbulent media will modify the IFL at the receiving side. We propose a new methodology to estimate this change and to exploit it for velocity estimation using acoustic signals. In this way, the amplitude based velocity estimation techniques can be substituted by non-stationary time – frequency signal processing. This technique proves to be more robust in terms of interferences and can provide a more detailed representation of any turbulent environment.

Index Terms **—** Adaptive waveforms, turbulence, Kolmogorov spectrum, instantaneous frequency law, wide band signals

1. INTRODUCTION

The potential of acoustic transducers for characterizing underwater dynamic phenomena can be considerably increased when migrating to nonintrusive measurement scenarios. In spite of the fact that there are a number of methods and techniques already in use [1], [2], [3], there are several drawbacks, mainly related to signal processing, that limit the measurement capabilities of existing nonintrusive systems.

The lack of an accurate, fast and low-cost method for absolute turbulent flows velocity measurements limits the use of such techniques in industry. One of the reasons is that conventional techniques still rely on the emission of short narrow-band acoustic pulses and take advantage of few transmission parameters, only (e.g. time of flight, flow induced amplitude changes…). It is therefore necessary to go beyond the conventional acoustic techniques and develop improved signal processing methods working in same operating scenarios.

On one side, the majority of measurement systems used amplitude based techniques: the amplitude changes due to the turbulence are directly employed in the flow rate estimation. On the other side, spectral information can be more robust to unwanted interferences (measurement noise, vibration, cross-talk…) and, if adequately processed, it can provide much more insight regarding the type and dynamics of the turbulent phenomena. This is crucial for flow measurements in a hydro power plant intake channel or in a nuclear reactor cooling circuit.

The turbulence is characterized by its energy variation with respect to the wave number (the Kolmogorov spectrum). This wideband analysis is jointly reflected in three spectral regions simultaneously (energetic, inertial and dissipative). Hence, wideband signal processing techniques need to be employed in order to provide the complete description of any turbulent environment.

The idea presented in this paper is to *construct waveforms with a particular frequency variation in time*. This waveform will be *adapted to the spectral content of the turbulence* that will be given by the IFL. The modifications undertaken by the IFL when the acoustic wave travels through the turbulent environment will provide a full description of the turbulence embedded in the flow and its sought-after parameters (flow velocity).

Flow velocities can be measured according to [3] by using two acoustic paths placed so that the turbulence conserves its dynamic properties (velocity and intensity). The emission of signals with IFLs adapted to the turbulent flow between the two acoustic paths will spawn received signals with similar IFLs, but with a certain time delay Δt between the two IFLs. This Δt is proportional with the flow velocity and can be estimated by correlating the extracted IFLs from the received signals.

Section 2 presents the theoretical aspects of combining the Kolmogorov spectrum concept with acoustic signal waveform generation (adaptive waveforms). In section 3, we

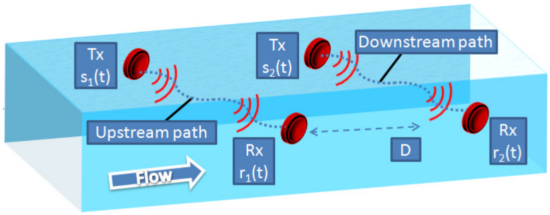

Fig. 1. Two identical acoustic paths.

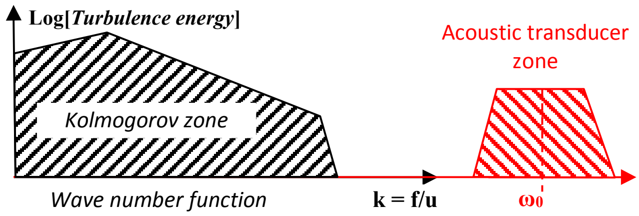

Fig. 2. Turbulence spectrum vs. transducer characteristic.

present an experiment in our reduced scale facility to test the proposed method for velocity estimation. This section also presents the results of our experiment and section 4 presents the conclusions of our work so far and further developments.

2. ADAPTIVE WAVEFORM TURBULENCE REPRESENTATION

The basic principle of the conventional acoustic technique for flow velocity measurement is illustrated in figure 1. Two pairs of acoustic transducers named *Tx* and *Rx* with the resonance frequencies f_c are placed on the sides of the turbulent flow section.

Acoustic pulses pass through the turbulent environment and reach the receiving acoustic transducer at the same f_c, but with different amplitude. The IFL of the received signal is therefore a constant line and no additional information about turbulence evolution is provided.

We can model the interaction between the acoustic signals and turbulent phenomena in several ways. First, the received signal *r(t)* can be modeled as a delayed, modulated and attenuated version of the emission, *s(t)* [4]:

$$r(t) = \alpha \cdot A(t) \cdot s(t-\tau) \qquad (1)$$

where *A(t)* corresponds to an envelope modulation, α is the attenuation coefficient of the signal in water [5] and τ is the time of flight between emission and reception. So far, the shape, content and duration of *s(t)* has not been regarded as important from the turbulence point of view.

However, in [6] the authors have shown that replacing short pulses by wideband signals can significantly improve the results in the case of obstacles in the acoustic path. The waveform used in [6] was the linear frequency modulation (chirp):

$$s(t) = A \cdot exp\left[j \cdot \left(\omega_0 \cdot t + \gamma \cdot t^2 / 2 \right) \right] \qquad (2)$$

where $f_0 + \gamma \cdot t$ is the signal's IFL.

The main conclusion derived from [6] is that *signals with physically driven IFLs* (IFLs adapted to the physics of the phenomena under study) are better suited for characterizing turbulent flows. Adaptive waveforms are constructed by investigating what happens inside a turbulent flow and give the turbulence a mathematical representation. In this way, we can establish a connection between the turbulence and the IFL. Based on the model described in (1) we consider that the received signal *r(t)* is the result of the convolution between the emission, *s(t)*, and the transfer function of turbulence, *h(t)*. This term is dependent on the dynamics of turbulent phenomena inside the flow, and therefore it carries information on the flow parameters, namely flow velocity. This simple model involving the transmitted signals can be written in time and frequency as [7]:

$$r(t) = (s * h)(t) \rightarrow R(f) = S(f) \cdot H(f) \qquad (3)$$

The term *H(f)* is very important because it represents the *changes suffered by the acoustic wave while interacting with the turbulent flow*. This can be viewed as the spectral signature of the turbulence, also known as the Kolmogorov spectrum [8]. The Komogorov spectrum represents the energy distribution of a turbulent flow as a function of the wave number, *k*. But what is the connection with flow velocity and acoustic signals?

Each fluid flow is also characterized by a dimensionless number *Re* called Reynolds number [9] and can be expressed as:

$$Re = \frac{\rho \cdot u \cdot L}{\mu} = \frac{k^2}{\varepsilon \cdot v}, \; k = \frac{\omega}{u} \qquad (4)$$

where ρ is the density of the fluid (in our case water), u is the velocity of the turbulent flow, L is the length of the measurement section, μ is the viscosity constant, ε is the energy dissipation constant, v is the cinematic viscosity and ω is the pulsation of the vortices created by turbulence, *dependent on the flow velocity, u.*

One can observe in Eq. (4) that the Kolmogorov spectrum limits can vary with flow velocity, i.e. *the bandwidth of turbulent phenomena is flow velocity dependent* (the wave number, *k,* of turbulence varies with the frequency of turbulence and the turbulent flow's velocity).

Figure 2 illustrates the connection between the two spectrums (signal and turbulence). The *Kolmogorov region* (left side) for a certain flow velocity *u,* is plotted alongside the *frequency characteristic of the acoustic transducers* (right side). The abscissa can be expressed both in terms of the wave number, *k*, and the acoustic transducer frequency characteristic. Both of them are connected by the flow and the signal velocity through water. However, these spectrums do not directly overlap or even cross over an therefore *the*

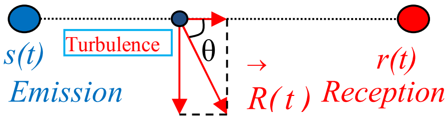

Fig. 3. Signal - turbulence interaction schematic.

full interaction between the turbulence and the acoustic signals does not occur. This is because the signal velocity through water can be far greater than flow velocity.

This spectral overlap cannot be achieved in case of conventional sine waveforms [1] since the envelope shape changes are not taken into account due narrowband. The use of wideband waveforms at the emission can create the desired spectral overlap: the signal's envelope is modified by the turbulence. Thus, if the envelope has an IFL found in the range of the Kolmogorov spectrum, *the turbulence will set its footprint on the IFL*. This effect was not seen because the pulse duration was very short in order to minimize the number of echoes [3].

Therefore, the flat shape (flat amplitude) of the emitted signal is replaced by a *waveform that has a bandwidth common with the turbulence in the flow*. The emitted signal *s(t)* from (1) and (3) has an instantaneous phase $\varphi(t)$. The phase changes as the signal passes along the acoustic path and the received signal *r(t)* will have a different instantaneous phase, $\varphi'(t)$. In other words, the phase shift of the emitted signal is dependent on the signal's velocity in water and the displacement vector of the flow, as it can be seen in (5):

$$s(t) = exp\left[j \cdot \varphi(t)\right]$$
$$r(t) = exp\left[j \cdot \varphi'(t)\right], \varphi'(t) = \varphi\left(t - \vec{R}(t) / c_{signal}\right) \quad (5)$$

where c_{signal} is the velocity of the acoustic signal in water and *R(t)* is the turbulence displacement vector defined as [10]:

$$\vec{R}(t) = R(t) \cdot cos\,\theta = \left(r_0 + u \cdot t + a \cdot t^2 / 2\right) \cdot cos\,\theta \quad (6)$$

where θ is the angle between the displacement vector and the acoustic path, r_0 is the initial starting point, u is the flow velocity and a is the acceleration of the flow. Replacing *R(t)* in (5) from (6), we calculate the dependence of the signal's phase on the flow velocity at the receiver:

$$\varphi'(t) = \varphi\left[t - \left(r_0 + u \cdot t + a \cdot t^2 / 2\right) \cdot cos\,\theta / c_{signal}\right] \quad (7)$$

All the elements from (7) provide the means to calculate the flow velocity using the phase of the received signals: the signal velocity in water is known, $r_0 = 0$ and the flow direction is perpendicular to the acoustic path:

$$\varphi'(t) = \varphi\left[t \cdot \left(1 - \left(u + a \cdot t / 2\right) \cdot cos\,\theta / c_{signal}\right)\right] \quad (8)$$

One can note that the term containing c_{signal} is very close to zero since c_{signal} is around 1500 m/s and u can be one hundred times lower. Therefore, *the ratio* u/c_{signal} *is very weak to generate significant changes on the IFL*. In order to reduce the influence of c_{signal}, the initial emitted phase $\varphi(t)$ must compensate the high values of c_{signal} with terms of higher power, such as a cubic law variation described by:

$$IFL(t) = a_0 + a_1 \cdot t + a_2 \cdot t^2 + a_3 \cdot t^3 \quad (9)$$

Conventional techniques use a flat IFL (just the a_0 term) and the turbulence footprint on the signals is very weak. This is why the IFL has to contain a particular shape that is best suited for the flow metering application. A first degree ILF (thus containing $a_0 + a_1 \cdot t$) does manage to merge the two zones in fig. 2 (Kolmogorov and acoustic), but it is done on a narrow scale, as turbulence is a wide band phenomena. This is why the emitted IFL has to contain terms of higher power. However, the choice for the third degree polynomial shape f the IFL is not random, as a cubic law is the only one that maximizes the impact of the u/c_{signal} term.

This cubic law IFL is illustrated in the figure 4. Choosing the parameters is application dependent. The term a_0 represents the vertical frequency offset. The second term, a_1 corresponds to an estimate of the flow velocity. For hydro power plants, this value is relatively known [3]. The second and third terms are given by the IFL's time and frequency boundaries and can be easily calculated.

The IFL from (9) will be employed in a double frequency and amplitude modulation/demodulation scheme. The emitted signal is an amplitude modulation between the resonance frequency of the acoustic transducers (carrier) and the IFL (the envelope). When travelling through the flow, the unknown turbulence spectral signature mixes with the known IFL envelope. Since the Kolmogorov spectrum and the acoustic (ultrasonic) transducer bandwidth are disjoints (see fig. 2), the carrier frequency will remain the same, and coherent demodulation is possible at the reception. In this way, it is easy to embed and extract the IFL into and from the signals:

$$s(t) = e^{(2 \cdot \pi \cdot j \cdot f_0 \cdot t)} \cdot e^{IFL_{emm}(t)}$$
$$r(t) = e^{(2 \cdot \pi \cdot j \cdot f_0 \cdot t)} \cdot e^{IFL_{rec}(t)} \quad (10)$$

The unknown turbulence spectral signature is retrieved by confronting the received (and estimated) IFL with the emitted one (known) as described in [10].

The IFL estimation algorithm is based on the local coherence of time, phase and frequency as described in [11]. This is better suited for short time phase modeling of order 3. Since the IFL is non-linear, the phase modeling is given by the Product High Order Ambiguity Function (PHAF) described in [12]. The algorithm is approximating the local time-frequency content in successive overlapping windows and merging the results into a continuous IFL, achieving thus a *global time frequency filtering*.

Using the coherence of time-phase-frequency information for IFL extraction proves to be more useful than one used in [10]. The reason is that although both methods divide the signal into overlapping windows, due to the cubic phase modeling cubic [11], the time-frequency resolution

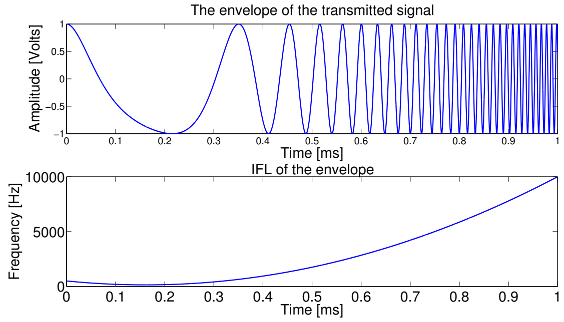

Fig. 4. The envelope of the transmitted signal and its IFL.

compromise of the spectrogram is eliminated, thus the time-phase-frequency coherence algorithm is less dependent on the window size.

Now imagine that there are two identical acoustic paths separated in space by a distance *D*, as illustrated in figure 1. The distance *D* is chosen such as the turbulence conserves its dynamic properties (namely the velocity). We know that it takes a certain amount of time, Δt, for the turbulence to travel between the two acoustic paths. When the turbulence passes in front of the two transducer pairs, it modifies the the IFLs of the received signals $r_1(t)$ and $r_2(t)$ envelopes, in such a way that the two IFLs appear to be shifted in time by Δt. The average flow velocity can be calculated by dividing the distance between the paths, D, and the time Δt between the two IFLs. This means that *at each transmitted waveform, the instantaneous average velocity of the flow can be calculated, thus faster than any conventional technique.*

3. RESULTS IN REDUCED SCALE EXPERIMENT

The tests were carried out in our reduced scale experimental facility. The facility consists in a large two cubic meter reinforced Plexiglas tank equipped with a recirculation pump that can replicate the context in figure 1. For our experiment, we used two pairs of 100 kHz transducers (named Upstream and Downstream), set apart by 11 centimeters in order to avoid the crosstalk between the transducers. In our study, it is crucial to properly select the adequate carrier frequency because of following two considerations: the signal's attenuation in water increases very fast with frequency and the turbulence generated in our experiment exhibits a bandwidth under 10 kHz, which leads to selecting two 100 kHz central frequency acoustic transducers. This was found out by submerging a hydrophone in the turbulent flow and "listening" to the turbulent flow (transfer function identification). The 100kHz carrier was modulated using SSB-AM (Single Side Band Amplitude Modulation). The envelope's cubic IFL is illustrated in figure 4.

The turbulence embedded in the water flow modifies the velocity profiles along the two acoustic paths, and implicitly

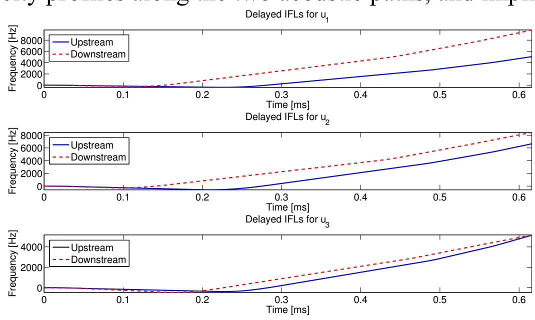

Fig. 5. IFLs from two adjacent acoustic paths corresponding to three different flow velocities: 0.6m/s (top); 1.1 m/s (middle); 2.7 m/s (bottom).

the two IFLs. For each received signal, the IFL is computed in order to show that the Upstream IFL is shifted from the Downstream IFL by a time delay, but maintaining the same shape. Several velocity profiles are investigated in order to determine if the time delay between the IFLs depends on the flow velocity.

Three flow velocities are simulated, u_1, u_2 and u_3, with $u_1 < u_2 < u_3$, and the corresponding three IFLs are illustrated in figure 5. We can observe that the IFLs corresponding to the two acoustic paths exhibit the same shape in all cases.

The time delay between the IFLs corresponds to the flow velocity. Since the signal to noise ratio is very high and having just one IFL in the signal (no close components), the continuous IFL's trajectory is obtained with a low computation time. Thus, the IFL extraction is robust and turbulence induced IFL changes are correctly estimated from the received signal: the delayed IFLs from figure 5 show that flow velocity estimations from turbulence are possible using the proposed adapting waveform technique.

4. CONCLUSIONS

This paper presented a new concept in turbulence representation using adaptive waveforms. The basic idea is to combine the physics of the turbulent flow and the acoustic signal properties in order to provide a more accurate and robust representation of the dynamics of turbulent flows, as well as in estimating an important parameter such as flow velocity.

Since turbulence manifests itself on the envelopes of the acoustic signals, amplitude modulated waveforms are transmitted in the turbulent flow. The spectrum of the transmitted signal's envelope represents the turbulence spectrum found embedded in the flow under investigation. In the time – frequency domain, the representation of the envelope's IFL yields more robust and relevant data regarding the dynamics of the turbulent flow. Future work will concentrate on developing a new algorithm for IFL estimation and a more thorough experimental validation in a hydro power plant configuration, taking into account the measurement section geometry for calculating IFL frequency bounds. Another research direction will try to find a correspondence between cubic IFL polynomial coefficients and several type of turbulence embedded in the flow.

In relation to previous work, the current study goes beyond the use of chirp signals previously presented in [6] and uses another approach to construct adapted waveforms for turbulent flows. Also, while in [10] the authors have shown that wideband signals with adapted IFLs can describe the evolution of fluid flows, the present study shows that is possible to calculate flow velocities starting from IFL estimation based on the time phase frequency coherence.

5. REFERENCES

[1] E.P. Papadakis, *Ultrasonic Instruments and Devices*, Academic Press, 1999.

[2] F. E. Jones, *Techniques and Topics in Flow Measurement*, CRC PressINC, 1995.

[3] J. Buermans, J. Lampa, D. Lemon, “Turbine flow measurement in low head plants – Acoustic scintillation flow meter: Why? How? Where?” Hydro 2009, Lyon, France.

[4] R. W. Lee, J. C. Harp, “Weak scattering in random media with applications in remote sensing,” IEEE Proceedings Vol. 57, pp. 406 – 537, n. 4, April 1969.

[5] A. Ishimaru, “Wave Propagation and Scattering in Random Media,” New York: Academic Press, 1978.

[6] I. Candel, C. Ioana, D. Lemon, B. Reeb, “Using wide band signals for obstacle path correction in acoustic scintillation flow meters,” The 11th Conference on Information Science, Signal Processing and their Applications, ISSPA 2012, Montreal, Canada, July 3 – 5 2012.

[7] L. Cohen, *Time-Frequency Analysis*, Prentice Hall, New Jersey, 1999.

[8] J. Jimenez, “The contributions of A. N. Kolmogorov to the theory of turbulence,” Arbor no. 704, pp. 589 – 606,August 2004.

[9] J. M. McDonough, *Introductory lectures on turbulence*, Department of Mechanical Engineering and Mechanics, University of Kentucky.

[10] Ion Candel, Cornel Ioana, Bertrand Reeb, Guy D’URSO, “Construction et Analyse des Signaux Non-stationnaires Adaptés à la Catactérisation des Phénomènes Turbulents”, XXIVéme Colloque Gretsi, Brest, 3 – 6 Septembre, 2013.

[11] Cornel Ioana, Jerome Mars, Alexandru Serbanescu, Srdjan Stankovic, “Time-Frequency-Phase Tracking Approach: Application to Underwater Signals in a Passive Context”, IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP) 2010, Dallas, USA.

[12] S. Barbarossa, A. Scaglione, G.B. Giannakis, “Product High-Order Ambiguity Function for Multicomponent Polynomial-Phase Signal Modeling”, IEEE Transactions on Signal Processing, vol. 46, No. 3, March 1998.